

Few active mechanisms of the $0\nu\beta\beta$ -decay and effective mass of Majorana neutrinos

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It is well known that there exist many mechanisms that may contribute to neutrinoless double beta decay. By exploiting the fact that the associated nuclear matrix elements are target dependent we show that, given definite experimental results on a sufficient number of targets, one can determine or sufficiently constrain all lepton violating parameters including the mass term. As a specific example we show that, assuming the observation of the $0\nu\beta\beta$ -decay in three different nuclei, e.g. ^{76}Ge , ^{100}Mo and ^{130}Te , and just three lepton number violating mechanisms (light and heavy neutrino mass mechanisms as well as R-parity breaking SUSY mechanism) being active, there are only four different solutions for the lepton violating parameters, provided that they are relatively real. In particular, assuming evidence of the $0\nu\beta\beta$ -decay of ^{76}Ge , the effective neutrino Majorana mass $|m_{\beta\beta}|$ can be almost uniquely extracted by utilizing other existing constraints (cosmological observations and tritium β -decay experiments). We also point out the possibility that the non-observation of the $0\nu\beta\beta$ -decay for some isotopes could be in agreement with a value of $|m_{\beta\beta}|$ in sub eV region. We thus suggest that it is important to have at least two different $0\nu\beta\beta$ -decay experiments for a given nucleus.

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I. INTRODUCTION

After the discoveries of oscillations of atmospheric, solar and terrestrial neutrinos, one has gained a lot of valuable information regarding the mixing matrix and the squared mass differences. The absolute scale of the neutrino mass cannot, however, be determined in such experiments. Our best hope for settling this important issue as well as solving a second challenging problem, i.e. whether the neutrinos are Majorana or Dirac particles, is the observation of neutrinoless double beta decay.

The total lepton number violating neutrinoless double beta decay ($0\nu\beta\beta$ -decay),

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-, \quad (1)$$

can take place only if the neutrino is a massive Majorana particle [1]. The measurement of the $0\nu\beta\beta$ -decay rate could, in principle, determine an absolute scale of neutrino mass, solve the neutrino mass hierarchy problem and provide information about the Majorana CP-violating phases of neutrinos.

The evidence for a $0\nu\beta\beta$ -decay of ^{76}Ge has been claimed by some authors of the Heidelberg-Moscow collaboration at Laboratori Nazionali del Gran Sasso [2] with

$$T_{1/2}^{0\nu}(^{76}\text{Ge}) = 2.23_{-0.31}^{+0.44} \times 10^{25} \text{ y}. \quad (2)$$

Such a claim has raised some criticism but none of the existing experiments can rule it out [3]. The only certain way to confirm or refute this claim is with additional

sensitive experiments [4], in particular the GERDA experiment [5], which plans to start taking data this year.

There is a general consensus that the $0\nu\beta\beta$ -decay has to be observed at different isotopes. Strong limits on the $0\nu\beta\beta$ -decay half-life have been achieved in NEMO3 [6] and CUORICINO [7] experiments:

$$T_{1/2}^{0\nu}(^{100}\text{Mo}) \geq 5.8 \times 10^{23} \text{ y}, \quad T_{1/2}^{0\nu}(^{130}\text{Te}) \geq 3.0 \times 10^{24} \text{ y}. \quad (3)$$

After neutrino oscillations established that the neutrinos are massive, non-degenerate and strongly admixed, naturally most people's attention has focused on the light neutrino mass mechanism of the $0\nu\beta\beta$ -decay.

It is well known, however, that the $0\nu\beta\beta$ -decay can be triggered by a plethora of other lepton number violating (LNV) mechanisms. Among these we should mention the exchange of heavy neutrinos, the exchange of SUSY superpartners with R-parity violating, leptoquarks, right-handed W-bosons or Kaluza-Klein excitations, among others, which have been discussed in the literature.

So the day after the $0\nu\beta\beta$ -decay is observed and, hopefully, established in a number of nuclei, the main question will be what is the dominant mechanism that triggers the decays.

Possibilities to distinguish at least some of the possible mechanisms include the analysis of angular correlations between the emitted electrons [8], study of the branching ratios of $0\nu\beta\beta$ -decays to ground and excited states [9], a comparative study of the $0\nu\beta\beta$ -decay and neutrinoless electron capture with emission of positron ($0\nu\text{EC}\beta^+$) [10] and analysis of possible connections with other lepton-flavor violating processes (e.g., $\mu \rightarrow e\gamma$) [11].

The main disadvantages of the above approaches are: small $0\nu\beta\beta$ -decay rates to excited states, suppressed $0\nu EC\beta^+$ -decay rates, experimental challenges to observe the produced X-rays or Auger electrons and the fact that most double β -decay experiments of the next generation are not sensitive to electron tracks.

In this paper we shall analyze what happens, if several mechanisms are active for the $0\nu\beta\beta$ -decay. We will show that all LNV parameters, including the most interesting mass term, can be determined provided that $0\nu\beta\beta$ data from traditional experiments involving a sufficient number of nuclear targets become available.

II. THE COEXISTENCE OF FEW LNV MECHANISMS OF THE $0\nu\beta\beta$ -DECAY

The subject of interest is a coexistence of the following LNV mechanisms of the $0\nu\beta\beta$ -decay: i) Light neutrino mass mechanism. ii) Heavy neutrino mass mechanism. Both mechanisms assume only left-hand current weak interactions. iii) The trilinear R-parity breaking SUSY mechanism generated by gluino exchange. For the sake of simplicity we shall assume that the lepton violating parameters are relatively real as, e.g., is the situation in the case CP conservation.

The inverse value of the $0\nu\beta\beta$ -decay half-life for a given isotope (A, Z) can be written as

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(E_0, Z) |\eta_\nu M_\nu^{0\nu} + \eta_N M_N^{0\nu} + \eta_{R_p} M_{R_p}^{0\nu}|^2. \quad (4)$$

Here, η_{ν, N, R_p} and $M_{\nu, N, R_p}^{0\nu}$ are, respectively, the LNV parameters and the nuclear matrix elements (NMEs), in the order given above. Each of the NMEs depends, in general, quite differently on the nuclear structure of the particular isotopes (A, Z), ($A, Z+1$) and ($A, Z+2$) under study.

$G^{0\nu}(E_0, Z)$ is the known phase-space factor (E_0 is the energy release), which include fourth power of axial-coupling constant $g_A = 1.25$. The $G^{0\nu}(E_0, Z)$ contain the inverse square of the nuclear radius R^{-2} , compensated by the factor R in $M^{0\nu}$. The assumed value of the nuclear radius is $R = r_0 A^{1/3}$ with $r_0 = 1.1 \text{ fm}$. The phase-space factors are tabulated in Ref. [12].

The lepton number violating mechanisms of interest together with corresponding nuclear matrix elements are presented briefly below.

A. Light Majorana neutrino exchange mechanism

In the case of light-neutrino mass mechanism of the $0\nu\beta\beta$ -decay we have

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} \quad (5)$$

Under the assumption of the mixing of three light massive Majorana neutrinos the effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ takes the form

$$m_{\beta\beta} = \sum_i^3 |U_{ei}|^2 \xi_i^{CP} m_i, \quad (\text{all } m_i \geq 0), \quad (6)$$

where U_{ei} is the first row of the neutrino mixing matrix and ξ_i^{CP} are unknown Majorana CP phases. m_i is the light neutrino mass ($m_i \leq 1 \text{ eV}$, $i=1, 2, 3$). In this case only left-handed weak interaction is taken into account.

The nuclear matrix element $M_\nu^{0\nu}$ consists of Fermi, Gamow-Teller and tensor parts as

$$M_\nu^{0\nu} = -\frac{M_{F(\nu)}}{g_A^2} + M_{GT(\nu)} + M_{T(\nu)}. \quad (7)$$

Here, g_A is axial-vector coupling constant. The Fermi, Gamow-Teller and tensor operators are defined in the usual way (see Eq. (10) below) with exchange potentials as given elsewhere [13]

B. Heavy Majorana neutrino exchange mechanisms

We assume that the neutrino mass spectrum include heavy Majorana states N with masses M_k much larger than the energy scale of the $0\nu\beta\beta$ -decay, $M_k \gg 1 \text{ GeV}$. These heavy states can mediate this process as the previous light neutrino exchange mechanism. The difference is that the neutrino propagators in the present case can be contracted to points and, therefore, the corresponding effective transition operators are local unlike in the light neutrino exchange mechanism with long range internucleon interactions.

The corresponding LNV parameter is given by

$$\eta_N = \sum_{k=4}^6 |U_{ek}|^2 \xi'_k \frac{m_p}{M_k}. \quad (8)$$

Here, m_p is the mass of proton. U_{ek} are elements of the neutrino mixing matrix associated with left-handed current interactions. ξ'_k are CP violating phases.

Separating the Fermi (F), Gamow-Teller (GT) and the tensor (T) contributions we write down

$$\begin{aligned} \mathcal{M}_N^{0\nu} &= -\frac{M_{F(N)}}{g_A^2} + M_{GT(N)} + M_{T(N)} \\ &= \langle 0_i^+ | \sum_{kl} \tau_k^+ \tau_l^+ \left[H_F^{(N)}(r_{kl})/g_A^2 \right. \\ &\quad \left. + H_{GT}^{(N)}(r_{kl})\sigma_{kl} - H_T^{(N)}(r_{kl})S_{kl} \right] | 0_f^+ \rangle, \quad (9) \end{aligned}$$

where

$$S_{kl} = 3(\vec{\sigma}_k \cdot \hat{\mathbf{r}}_{kl})(\vec{\sigma}_l \cdot \hat{\mathbf{r}}_{kl}) - \sigma_{kl}, \quad \sigma_{kl} = \vec{\sigma}_k \cdot \vec{\sigma}_l. \quad (10)$$

The radial parts of the exchange potentials can be found elsewhere [12].

C. R-parity breaking SUSY mechanism

In the SUSY models with R-parity non-conservation one encounters LNV couplings which may also trigger the $0\nu\beta\beta$ decay. Recall, that R-parity is a multiplicative quantum number defined by $R = (-1)^{2S+3B+L}$ (S,B,L are spin, baryon and lepton number). Ordinary particles have $R = +1$ while their superpartners $R = -1$. The LNV couplings emerge in this class of SUSY models from the R-parity breaking part of the superpotential

$$W_{R_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \mu_i L_i H_2, \quad (11)$$

where L, Q stand for lepton and quark $SU(2)_L$ doublet left-handed superfields, while E^c, D^c for lepton and down quark singlet superfields. This results in a lepton violating parameter entering the neutrinoless double beta decay, η_{R_p} .

For simplicity we concentrate below on the trilinear λ' couplings and write $\eta_{R_p} = \eta_{\lambda'}$. Under reasonable assumptions the gluino exchange dominates [14]. We have

$$\eta_{\lambda'} = \frac{\pi\alpha_s}{6} \frac{\lambda'_{211}}{G_F^2 m_{\tilde{d}_R}^4} \frac{m_p}{m_{\tilde{g}}} \left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}} \right)^2 \right]^2. \quad (12)$$

Here, G_F is the Fermi constant, $\alpha_s = g_3^2/(4\pi)$ is $SU(3)_c$ gauge coupling constant. $m_{\tilde{u}_L}, m_{\tilde{d}_R}$ and $m_{\tilde{g}}$ are masses of the u-squark, d-squark and gluino, respectively.

At the hadron level we assume dominance of the pion-exchange mode [14, 15]. We denote the $0\nu\beta\beta$ -decay nuclear matrix element, $\mathcal{M}_{R_p}^{0\nu}$, of Eq. (4) as $\mathcal{M}_{\lambda'}^{0\nu}$ with

$$\mathcal{M}_{\lambda'}^{0\nu} = c_A \left[\frac{4}{3} \alpha^{1\pi} (M_T^{1\pi} - M_{GT}^{1\pi}) + \alpha^{2\pi} (M_T^{2\pi} - M_{GT}^{2\pi}) \right] \quad (13)$$

with $c_A = m_A^2/(m_p m_e)$ ($m_A = 850$ MeV). The structure coefficients of the one-pion $\alpha^{1\pi}$ and two-pion mode $\alpha^{2\pi}$ are [14, 15]: $\alpha^{1\pi} = -0.044$ and $\alpha^{2\pi} = 0.20$. The partial nuclear matrix elements of the R_p SUSY mechanism for the $0\nu\beta\beta$ -decay process are:

$$\begin{aligned} M_{GT}^{k\pi} &= \langle 0_f^+ | \sum_{k \neq l} \tau_k^+ \tau_l^+ H_{GT}^{k\pi}(r_{kl}) \sigma_i \cdot \sigma_j, | 0_i^+ \rangle, \\ M_T^{k\pi} &= \langle 0_f^+ | \sum_{k \neq l} \tau_k^+ \tau_l^+ H_T^{k\pi}(r_{kl}) S_{kl} | 0_i^+ \rangle \end{aligned} \quad (14)$$

with the radial functions given elsewhere [14, 15]. Under these assumptions the obtained nuclear matrix elements are given in table I

In obtaining the nuclear matrix elements we used the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA) [16] to calculate nuclear matrix elements (NMEs) $M_{\nu}^{0\nu}, M_N^{0\nu}$ and $M_{\lambda'}^{0\nu}$. The SRQRPA takes into account the Pauli exclusion principle and conserves the mean particle number in correlated ground state. For A=76 and 100 nuclear systems the single-particle model space consists of $0 - 5\hbar\omega$ oscillator shells and for A=130 nuclear system we used

TABLE I. The $0\nu\beta\beta$ -decay NMEs calculated with the Selfconsistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA). The Coupled Cluster Method (CCM) short-range correlations calculated with CD-Bonn potential are taken into account [17]. $g_A = 1.25$.

Nucl. trans.	$G^{0\nu}(E_0, Z) [y^{-1}]$	$M_{\nu}^{0\nu}$	$M_N^{0\nu}$	$M_{\lambda'}^{0\nu}$
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	7.98×10^{-15}	5.82	412.	596.
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	5.73×10^{-14}	5.15	404.	589.
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	5.54×10^{-14}	4.70	385.	540.

$0 - 5\hbar\omega$ shells plus $0i_{11/2}$ and $0i_{13/2}$ levels both for protons and neutrons. In the calculation of the $0\nu\beta\beta$ -decay NMEs the two-nucleon short-range correlations derived from same potential as residual interactions, namely from the CD-Bonn potential [17], are considered. The calculated NMEs are given in Table I.

III. CALCULATION AND DISCUSSION

A. Dominance of a single $0\nu\beta\beta$ -decay mechanism

Commonly, it is assumed that a single LNV mechanism is responsible for the $0\nu\beta\beta$ -decay. Let suppose it is the light neutrino mass ($m_{\beta\beta}$) or heavy neutrino mass (η_N) mechanism. Then, the $0\nu\beta\beta$ -decay half-lives T_1 and T_2 for two nuclear systems are related with equation

$$|m_{\beta\beta}| = \frac{m_e}{|M_i^{\nu}| \sqrt{T_i} G_i}, |\eta_N| = \frac{1}{|M_i^{\eta_N}| \sqrt{T_i} G_i} \quad (15)$$

Here, G_i is the kinematical factor, while M_i^{ν} and $M_i^{\eta_N}$ are nuclear matrix elements associated with $m_{\beta\beta}$ and η_N parameters, respectively for the target i .

B. Two active $0\nu\beta\beta$ -decay mechanisms

We will now move into the case of two competing $0\nu\beta\beta$ -decay mechanisms representing by the LNV parameters $m_{\beta\beta}$ and η , η could be η_N or η_{R_p} . In this case we have four different sets of two linear equations:

$$\frac{\pm 1}{\sqrt{T_1} G_1} = \frac{m_{\beta\beta}}{m_e} M_1^{\nu} + \eta M_1^{\eta}, \frac{\pm 1}{\sqrt{T_2} G_2} = \frac{m_{\beta\beta}}{m_e} M_2^{\nu} + \eta M_2^{\eta}. \quad (16)$$

For the absolute value of the LNV parameters we find two different solutions,

$$\begin{aligned} |m_{\beta\beta}| &= \left| \frac{m_e}{M_1^{\nu} \sqrt{T_1} G_1} \frac{M_1^{\nu} M_2^{\eta}}{(M_1^{\nu} M_2^{\eta} - M_2^{\nu} M_1^{\eta})} \right. \\ &\quad \left. \pm \frac{m_e}{M_2^{\nu} \sqrt{T_2} G_2} \frac{M_2^{\nu} M_1^{\eta}}{(M_1^{\nu} M_2^{\eta} - M_2^{\nu} M_1^{\eta})} \right| \\ |\eta| &= \left| \frac{1}{M_1^{\eta} \sqrt{T_1} G_1} \frac{M_1^{\eta} M_2^{\nu}}{(M_1^{\eta} M_2^{\nu} - M_2^{\eta} M_1^{\nu})} \right| \end{aligned} \quad (17)$$

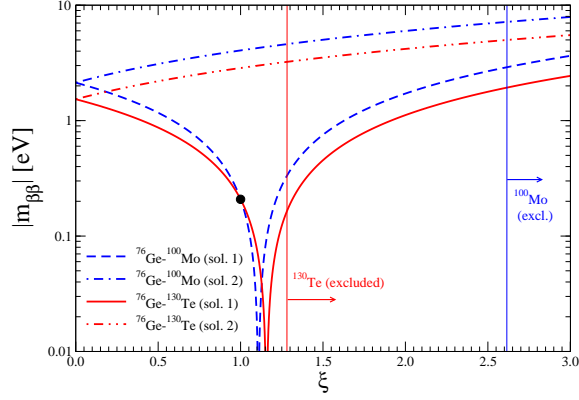


FIG. 1. The effective Majorana mass of neutrinos in the case of two active mechanisms of the $0\nu\beta\beta$ -decay, namely light and heavy neutrino exchange mechanisms, as function of parameter ξ (see Eq. (19)). $T_{1/2}^{0\nu}(^{76}\text{Ge}) = 2.23 \times 10^{25}$ y [2] is assumed. Solutions 1 and 2 were obtained for equal and opposite signs on the left hand side of Eqs. (16), respectively. The bold point indicates the value of $m_{\beta\beta}$, if the light neutrino exchange is the only active mechanism.

$$\pm \frac{1}{M_2^\eta \sqrt{T_2 G_2}} \frac{M_2^\eta M_1^\nu}{(M_1^\eta M_2^\nu - M_2^\eta M_1^\nu)} \Big|, \quad (18)$$

We note, however, that for $\eta = 0$ Eqs. (17) and (18) are reduced to Eq. (15).

By assuming now $\eta \equiv \eta_N$ the solutions for $|m_{\beta\beta}|$ will be analyzed for two different combinations of nuclear systems, namely with $A = 76$ and 100 (case I) and $A = 76$ and 130 (case II). An additional assumption is that the $0\nu\beta\beta$ -decay half-life of ^{76}Ge has been measured with $T_{1/2}^{0\nu}(^{76}\text{Ge})$ given in (2). In Fig. 1 the two solutions for $|m_{\beta\beta}|$ are plotted as function of ξ , where

$$\xi = \frac{|M_1^\nu| \sqrt{T_1 G_1}}{|M_2^\nu| \sqrt{T_2 G_2}}, \quad (19)$$

Indices 1 and 2 denote the above cases I and II respectively. The parameter ξ represents the unknown half-life of the $0\nu\beta\beta$ -decay of ^{100}Mo or ^{130}Te . We note that for $\xi = 1$ the solution for active only light neutrino mass mechanism given by Eq. (15) is reproduced and that $\xi = 0$ means non-observation of the $0\nu\beta\beta$ -decay for a considered isotope.

By glancing the Fig. 1 we see that for both combinations of nuclear systems the two solutions for $|m_{\beta\beta}|$ exhibit similar behavior. For $\xi \approx 1.1$ one of the solution can be even equal to zero. The second solution predicts $m_{\beta\beta} > 1$ eV. The current lower limits on the half-life of the $0\nu\beta\beta$ -decay of ^{100}Mo or ^{130}Te restrict the effective mass of Majorana neutrinos to intervals (0.0 eV, 7.2 eV) and (0.0 eV, 3.2 eV), respectively. So, within the considered assumptions the claim of evidence of the $0\nu\beta\beta$ -decay of ^{76}Ge [2] is compatible also with inverted ($m_i < 50$ meV) or normal ($m_i \approx \text{few meV}$) hierarchy of neutrino masses. From Fig. 1 it follows that a small improvement of the current half-life limit for ^{130}Te up to

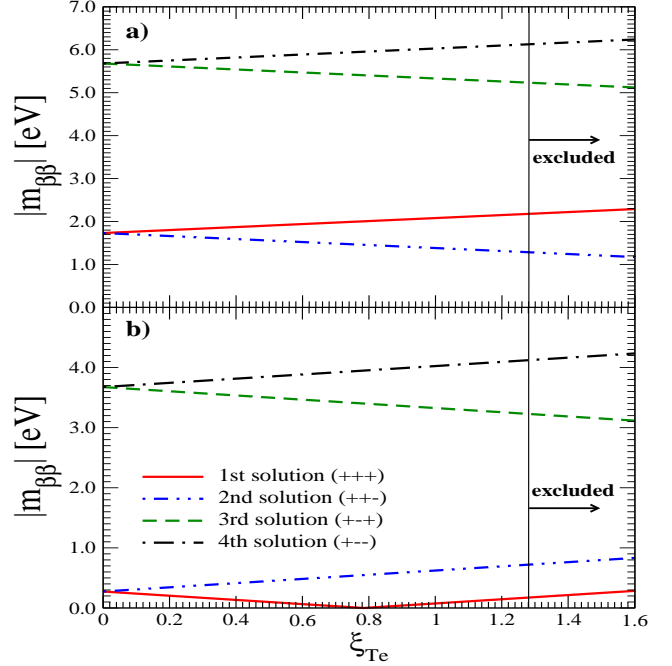


FIG. 2. The effective Majorana mass of neutrinos in the case of three active mechanisms of the $0\nu\beta\beta$ -decay, namely light and heavy neutrino exchange mechanisms and R-parity breaking SUSY mechanism with gluino exchange, as function of parameter ξ_{Te} . Nuclear systems with $A = 76$, 100 and 130 are considered. $T_{1/2}^{0\nu}(^{76}\text{Ge})$ is the same as in Fig. 1. $\xi_{\text{Mo}} = 2.6$ and $\xi_{\text{Mo}} = 1.2$ are assumed in upper (a) and lower (b) panels, respectively. For each solution there are given in brackets signs in front of term $1/\sqrt{T_i G_i}$ in Eqs.(20) for ^{76}Ge , ^{100}Mo and ^{130}Te .

value 4.1×10^{24} y ($\xi_{\text{Te}} \simeq 1.1$) would exclude these possibilities. Another finding is that the non-observation of the $0\nu\beta\beta$ -decay for ^{100}Mo or ^{130}Te (i.e., $\xi = 0$) cannot rule out the claim for evidence of the $0\nu\beta\beta$ -decay of ^{76}Ge . This can only happen if, in a more sensitive Ge experiment like GERDA or Majorana, no $0\nu\beta\beta$ -decay signal will be registered.

C. Three active $0\nu\beta\beta$ -decay mechanisms

In the case of three active $0\nu\beta\beta$ -decay mechanisms represented by the LNV parameters $m_{\beta\beta}$, η_N and $\eta_{\lambda'}$ assuming the measurement of the life time of the $0\nu\beta\beta$ -decay of three isotopes one obtains a set of three linear equations:

$$\frac{\pm 1}{\sqrt{T_i G_i}} = \frac{m_{\beta\beta}}{m_e} M_i^\nu + \eta_N M_i^\eta + \eta_{\lambda'} M_i^{\lambda'}, \quad i = 1, 2, 3 \quad (20)$$

The equations (20) admit a set of four different solutions, which are exhibited in Fig. 2. The upper and lower panels correspond to $\xi_{\text{Mo}} = 2.6$ (current limit) and $\xi_{\text{Mo}} = 1.2$, respectively. The allowed ranges of $m_{\beta\beta}$ are

as follows: i) (1.3, 2.2) eV and (5.2, 6.1) eV for upper panel, ii) (0.0, 1.7) eV and (3.2, 4.1) eV for lower panel. We see that for a given value of ξ_{Te} allowed intervals for $|m_{\beta\beta}|$ depend strongly on the value of ξ_{Mo} . The upper two solutions determining the second interval are already excluded by the Mainz and Troitsk tritium experiments [18]. In case the claim of evidence of the $0\nu\beta\beta$ decay of ^{76}Ge would be ruled out by other experiments, i.e. for larger value of $T_{1/2}^{0\nu}(^{76}\text{Ge})$, they would decrease and might be important.

IV. CONCLUSIONS

It has been shown that the extraction of the most important neutrino mass contribution, entering neutrinoless double beta decay, can be disentangled from the other mechanisms, if and when the decay rates in a sufficient number of nuclear targets become available. In the present calculation, to simplify the exposition, we restricted ourselves in the special case of no right handed currents and made the assumption that the LNV parameters are relatively real. To be more specific, in addition to the standard light neutrino mass mechanism of the $0\nu\beta\beta$ -decay, we considered two additional LNV mechanisms, namely those involving the exchange of heavy neutrinos and R-parity breaking SUSY with gluino exchange. We find that this improved analysis leads to completely different results compared to those of one mechanism at a time. It is now possible that larger values of $|m_{\beta\beta}|$ can be consistent with the data, since the contribution of the other mechanisms could be interfering with it destruc-

tively.

We specifically discussed the extracted value of the effective Majorana neutrino mass, $m_{\beta\beta}$, assuming the claim of evidence of the $0\nu\beta\beta$ -decay of ^{76}Ge [2] as a function of half-life data for the two promising nuclei, (^{100}Mo and ^{130}Te). We showed that in an analysis including two and three nuclear systems there are 2 and 4 different possible solutions for $|m_{\beta\beta}|$, respectively. One of the solutions leads to small values of $|m_{\beta\beta}|$, when all mechanisms add up coherently. This is compatible also with inverted ($m_i < 50$ meV) or normal ($m_i \approx \text{few meV}$) hierarchy of neutrino masses. Other solutions, however, allow quite large values of $|m_{\beta\beta}|$, even larger than 1 eV. These can, of course, be excluded by cosmology and tritium β -decay experiments. It may not, however, be possible to exclude these solutions, if the claim of evidence for ^{76}Ge would be ruled out by future experiments, since, then, the values we obtain become smaller than those of the other experiments.

It is thus important that experiments involving as many different targets as possible be pursued. Furthermore, in the presence of interference between the various mechanisms, the availability of reliable nuclear matrix elements becomes more imperative.

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- [1] J. Schechter and J.W.F. Valle, Phys. Rev. D **25**, 2951 (1982); M. Hirsch, H.V. Klapdor-Kleingrothaus, S. Kovalenko, Phys. Lett. B **372**, 8 (1996).
 - [2] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, Mod. Phys. Lett. A **21**, 1547 (2006); H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney, I. V. Krivosheina, Mod. Phys. Lett. A **16**, 2409 (2001).
 - [3] A. Faessler, G.L. Fogli, E. Lisi, V. Rodin, F. Šimkovic, Phys. Rev. D **79**, 053001 (2009).
 - [4] F. T. Avignone, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008).
 - [5] I. Abt et al. (GERDA Collaboration), arXiv:hep-ex/0404039.
 - [6] R. Arnold et al. (NEMO Collaboration), Phys. Rev. Lett. **95**, 182302 (2005).
 - [7] C. Arnaboldi et al. (CUORE Collaboration), Phys. Lett. B **584**, 260 (2004).
 - [8] M. Doi, T. Kotani, H. Nishiura and E. Takasugi, Prog. Theor. Phys. **69**, 602 (1983); F. Deppisch, Ch. Jackson, I. Nasteva, S. Soldner-Rembold, Prog. Part. Nucl. Phys. **64**, 278 (2010).
 - [9] S. M. Bilenky, J.A. Grifols, Phys. Lett. B **550**, 154 (2002); F. Šimkovic, A. Faessler, Prog. Part. Nucl. Phys. **48**, 201 (2002); F. Deppisch, H. Päs, Phys. Rev. Lett. **98**, 232501 (2007).
 - [10] M. Hirsch, K. Muto, T. Oda and H. V. Klapdor-Kleingrothaus, Z. Phys. A **347**, 151 (1994).
 - [11] V. Cirigliano, A. Kurylov, M. J. Ramsey-Musolf and P. Vogel, Phys. Rev. Lett. **93**, 231802 (2004).
 - [12] F. Šimkovic, G. Pantis, J.D. Vergados, and A. Faessler, Phys. Rev. C **60**, 055502 (1999).
 - [13] F. Šimkovic, A. Faessler, V.A. Rodin, P. Vogel, and J. Engel, Phys. Rev. C **77**, 045503 (2008).
 - [14] A. Wodecki, W.A. Kaminski, F. Šimkovic, Phys. Rev. D **60**, 115007 (1999).
 - [15] A. Faessler, S. Kovalenko, F. Šimkovic, and J. Schwieger, Phys. Rev. Lett. **78**, 183 (1997); A. Faessler, S. Kovalenko, and F. Šimkovic, Phys. Rev. D **58**, 115004 (1998).
 - [16] D.S. Delion, J. Dukelsky, and P. Schuck, Phys. Rev. C **55**, 2340 (1997); F. Krmpotić et al., Nucl. Phys. A **637**, 295 (1998).
 - [17] F. Šimkovic, A. Faessler, H. Mütter, V. Rodin, and M. Stauf, Phys. Rev. C **79**, 055501 (2009).
 - [18] E. W. Otten and C. Weinheimer, Rep. Prog. Phys. **71**, 086201 (2008).